EVALUATION OF n + 27Al CROSS SECTIONS FOR THE ENERGY RANGE 1.0E-11 to 150 MeV

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This evaluation provides a complete representation of the nuclear data needed for transport, damage, heating, radioactivity, and shielding applications over the incident neutron energy range from 1.0E-11 to 150 MeV. The discussion here is divided into the region below and above 20 MeV.

INCIDENT NEUTRON ENERGIES < 20 MeV

Below 20 MeV the evaluation is based completely on the ENDF/B-VI.1 (Release 3) evaluation by Young (Yo94).

INCIDENT NEUTRON ENERGIES > 20 MeV

The ENDF/B-VI Release 3 evaluation extends to 40 MeV and includes cross sections and energy-angle data for all significant reactions. The present evauation utilizes a more compact composite reaction spectrum representation above 20 MeV in order to reduce the length of the file. No essential data for applications is lost with this representation. Additionally, we have modified the neutron reaction cross sections slightly to improve agreement with data above 20 MeV.

The evaluation above 20 MeV utilizes MF=6, MT=5 to represent all reaction data. Production cross sections and emission spectra are given for neutrons, protons, deuterons, tritons, alpha particles, gamma rays, and all residual nuclides produced (A>5) in the reaction chains. To summarize, the ENDF sections with non-zero data above En = 20 MeV are:

MF=3	MT=	1	Total Cross Section
	MT=	2	Elastic Scattering Cross Section
	MT=	3	Nonelastic Cross Section
	MT=	5	Sum of Binary (n,n') and (n,x) Reactions
MF=4	MT=	2	Elastic Angular Distributions
MF=6	MT=	5	Production Cross Sections and Energy-Angle Distributions for Emission Neutrons, Protons, Deuterons, and Alphas; and Angle-Integrated Spectra for Gamma Rays and Residual Nuclei That Are Stable Against Particle Emission

The evaluation is based on nuclear model calculations that have been benchmarked to experimental data, especially for n + Al27 and p + Al27 reactions (Ch97). We use the GNASH code system (Yo92), which utilizes Hauser-Feshbach statistical, preequilibrium and direct-reaction theories. Spherical optical model calculations are used to obtain particle transmission coefficients for the Hauser-Feshbach calculations, as well as for the elastic neutron angular distributions.

Cross sections and spectra for producing individual residual nuclei are included for reactions that exceed a cross section of approximately 1 nb at any energy. The energy-angle-correlations for all outgoing particles are based on Kalbach systematics

(Ka88).

A model was developed to calculate the energy distributions of all recoil nuclei in the GNASH calculations (Ch96). The recoil energy distributions are represented in the laboratory system in MT=5, MF=6, and are given as isotropic in the lab system. All other data in MT=5,MF=6 are given in the center-of-mass system. This method of representation utilizes the LCT=3 option approved at the November, 1996, CSEWG meeting..

Preequilibrium corrections were performed in the course of the GNASH calculations using the exciton model of Kalbach (Ka77, Ka85), validated by comparison with calculations using Feshbach, Kerman, Koonin (FKK) theory [Ch93]. Discrete level data from nuclear data sheets were matched to continuum level densities using the formulation of Ignatyuk (Ig75) and pairing and shell parameters from the Cook (Co67) analysis. Neutron and charged-particle transmission coefficients were obtained from the optical potentials, as discussed below. Gamma-ray transmission coefficients were calculated using the Kopecky-Uhl model (Ko90).

The neutron total cross section was evaluated from available experimental data. From 20 - 40 MeV, the existing ENDF/B-VI.3 total cross section evaluation of Young was adopted; from 40 - 150 MeV, the evaluation was based primarily on Finlay's 1993 measurements (Fi93). The optical potential of Petler (Pe85), specially developed for n+Al elastic scattering, was used for neutrons up to 60 MeV, and above this energy the Madland global potential (Ma88) was used. For incident protons, the Petler neutron potential was modified to account for proton scattering up to 60 MeV, and again the Madland global potential was used at higher energies. For deuterons, the potential of Perey and Perey (Pe63) was used at all energies, and for tritons the Becchetti and Greenlees potential (Be71) was adopted. Finally, the potential of Arthur and Young (Ar80), based on the work of Lemos (Le72), was used for alpha particles at all energies. DWBA calculations were performed for inelastic scattering to low-lying states using the DWUCK code.

While the above optical potentials did describe the experimental neutron and proton nonelastic cross section data fairly well, we modified these theoretical predictions slightly to better agree with the measurements, and renormalized the transmission coefficients accordingly.

The present evaluation was greatly facilitated by Benck et al.'s (Be97) measurements of charged-particle producing reactions on Al for incident neutrons at 63 MeV at Louvain-la-Neuve, Belgium. Since these data represent the only neutron-induced emission spectra above 20 MeV, they have been invaluable for guiding, and testing, our calculations. The proton, triton, and alpha emission spectra in the Benck et al. measurements are described very well. However, our deuteron emission calculations compare poorly with the measurements. Fortunately this has only a small practical impact since deuteron emission is small compared to proton emission, and our calculated emission spectrum approximates the measured deuteron energy deposition (production cross section times average energy) reasonably well, which is important for heating calculations. The combination of equilibrium and preequilibrium reaction mechanisms included in the GNASH code account for the measured data rather well.

As an independent validation of our GNASH calculations using the exciton model, we have also performed FKK calculations. This was done by implementing a multistep reaction theory recently developed by Koning and Chadwick, which is particularly suited to the simultaneous calculation of neutron and proton emission. The FKK theory describes the forward-peaking very well, as do our exciton model calculations using the phenomenological Kalbach angular distribution systematics.

As additional validation of the models used in our neutron evaluation, extensive comparisons were made to higher energy proton-induced measurements. In particular, the neutron and charged-particle emission spectra measured at the University of Maryland (Kalend et al. and Wu et al.) for 90-MeV protons, by Meier at Los Alamos for 113-MeV protons, and Bertrand and Peelle for 61-MeV protons are all reproduced reasonably by the present analysis (Ch97).

Another useful test of our model calculations, particularly for radionuclide production, can be made by comparing our theoretical predictions of discrete gamma-ray emission in Al27(n,xngamma) reactions with the recent LANSCE/WNR data taken by Vonach, Haight, and collaborators (Vo94) using the white neutron source. Preliminary comparisons show reasonably good agreement.

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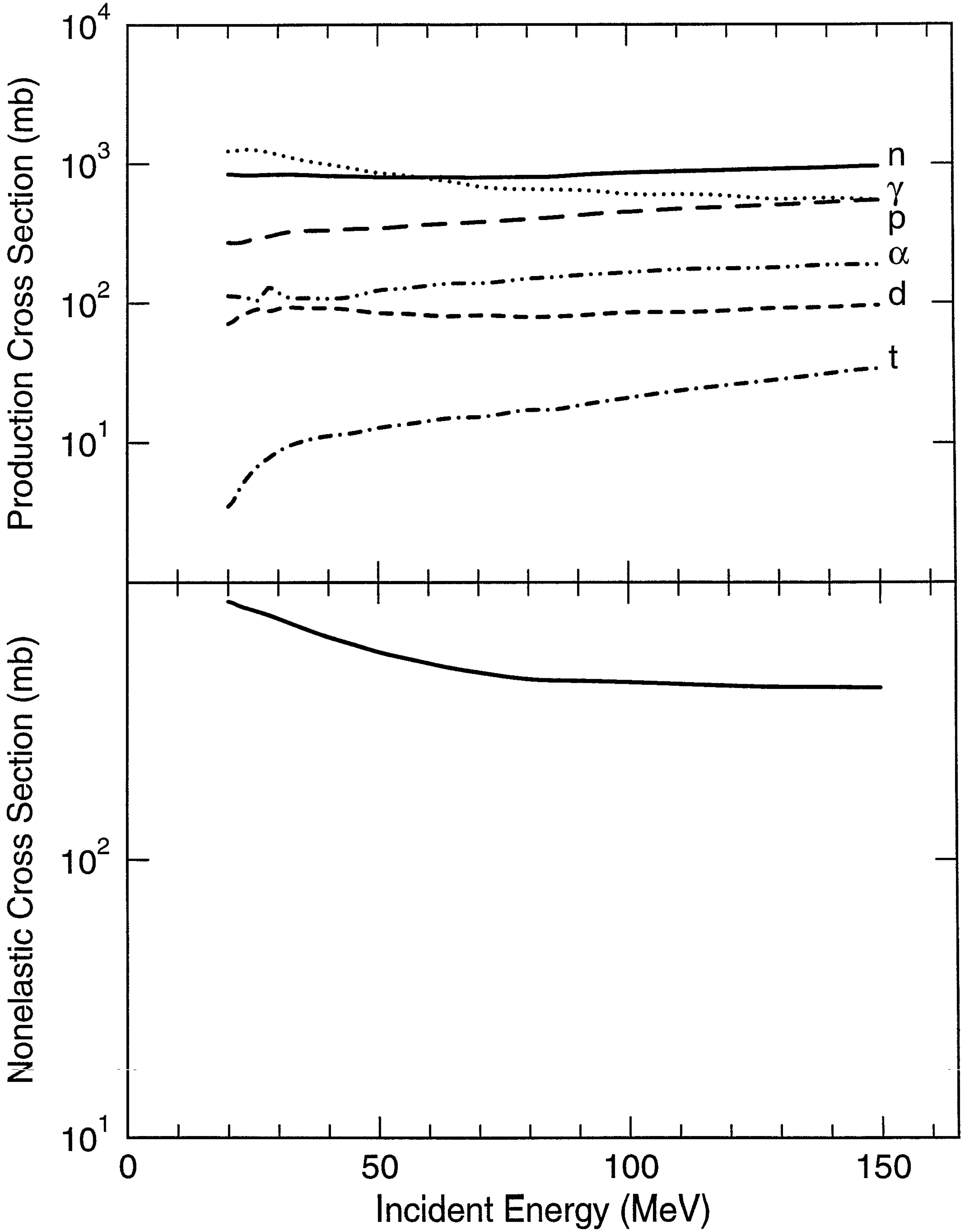
13027 = TARGET 1000Z+A (if A=0 then elemental)
1 = PROJECTILE 1000Z+A
Nonelastic, elastic, and Production cross sections for A<5 ejectiles in barns:

Energy	nonelas	elastic	neutron	proton	deuteron	triton	helium3	alpha	gamma
2.000E+01	8.550E-01	9.450E-01	8.426E-01	2.713E-01	7.090E-02	3.483E-03	0.000E+00	1.125E-01	1.229E+00
2.200E+01	8.264E-01	9.973E-01	8.334E-01	2.707E-01	7.924E-02	4.474E-03	0.000E+00	1.111E-01	1.248E+00
2.400E+01	8.030E-01	1.046E+00	8.281E-01	2.801E-01	8.539E-02	5.698E-03	0.000E+00	1.087E-01	1.269E+00
2.600E+01	7.823E-01	1.090E+00	8.312E-01	2.939E-01	9.042E-02	6.831E-03	0.000E+00	1.047E-01	1.247E+00
2.800E+01	7.624E-01	1.123E+00	8.370E-01	3.004E-01	8.721E-02	7.706E-03	0.000E+00	1.286E-01	1.214E+00
3.000E+01	7.396E-01	1.146E+00	8.386E-01	3.129E-01	9.084E-02	8.653E-03	0.000E+00	1.192E-01	1.170E+00
3.500E+01	6.828E-01	1.187E+00	8.341E-01	3.298E-01	9.187E-02	1.027E-02	0.000E+00	1.085E-01	1.060E+00
4.000E+01	6.339E-01	1.186E+00	8.181E-01	3.320E-01	9.166E-02	1.114E-02	0.000E+00	1.075E-01	9.888E-01
4.500E+01	5.967E-01	1.152E+00	8.133E-01	3.405E-01	8.859E-02	1.169E-02	0.000E+00	1.116E-01	9.244E-01
5.000E+01	5.610E-01	1.114E+00	8.022E-01	3.439E-01	8.447E-02	1.271E-02	0.000E+00	1.226E-01	8.609E-01
5.500E+01	5.349E-01	1.058E+00	7.991E-01	3.545E-01	8.356E-02	1.344E-02	0.000E+00	1.268E-01	8.305E-01
6.000E+01	5.108E-01	9.992E-01	8.024E-01	3.655E-01	8.116E-02	1.423E-02	0.000E+00	1.330E-01	7.820E-01
6.500E+01	4.895E-01	9.405E-01	7.993E-01	3.728E-01	8.006E-02	1.499E-02	0.000E+00	1.382E-01	7.405E-01
7.000E+01	4.738E-01	8.812E-01	7.969E-01	3.804E-01	8.111E-02	1.517E-02	0.000E+00	1.382E-01	6.877E-01
7.500E+01	4.594E-01	8.206E-01	8.017E-01	3.892E-01	8.022E-02	1.605E-02	0.000E+00	1.425E-01	6.618E-01
8.000E+01	4.484E-01	7.616E-01	8.034E-01	3.998E-01	7.876E-02	1.706E-02	0.000E+00	1.492E-01	6.562E-01
8.500E+01	4.439E-01	7.030E-01	8.081E-01	4.105E-01	7.937E-02	1.720E-02	0.000E+00	1.524E-01	6.520E-01
9.000E+01	4.424E-01	6.496E-01	8.313E-01	4.244E-01	8.069E-02	1.834E-02	0.000E+00	1.575E-01	6.454E-01
9.500E+01	4.401E-01	5.979E-01	8.495E-01	4.401E-01	8.298E-02	1.958E-02	0.000E+00	1.612E-01	6.299E-01
1.000E+02	4.372E-01	5.508E-01	8.625E-01	4.500E-01	8.472E-02	2.079E-02	0.000E+00	1.650E-01	6.057E-01
1.100E+02	4.310E-01	4.640E-01	8.816E-01	4.729E-01	8.505E-02	2.335E-02	0.000E+00	1.733E-01	6.025E-01
1.200E+02	4.244E-01	4.036E-01	8.990E-01	4.886E-01	8.740E-02	2.565E-02	0.000E+00	1.762E-01	5.884E-01
1.300E+02	4.203E-01	3.527E-01	9.184E-01	5.061E-01	9.098E-02	2.815E-02	0.000E+00	1.790E-01	5.568E-01
1.400E+02	4.197E-01	2.973E-01	9.358E-01	5.278E-01	9.237E-02	3.109E-02	0.000E+00	1.863E-01	5.665E-01
1.500E+02	4.179E-01	2.651E-01	9.607E-01	5.459E-01	9.533E-02	3.361E-02	0.000E+00	1.873E-01	5.533E-01

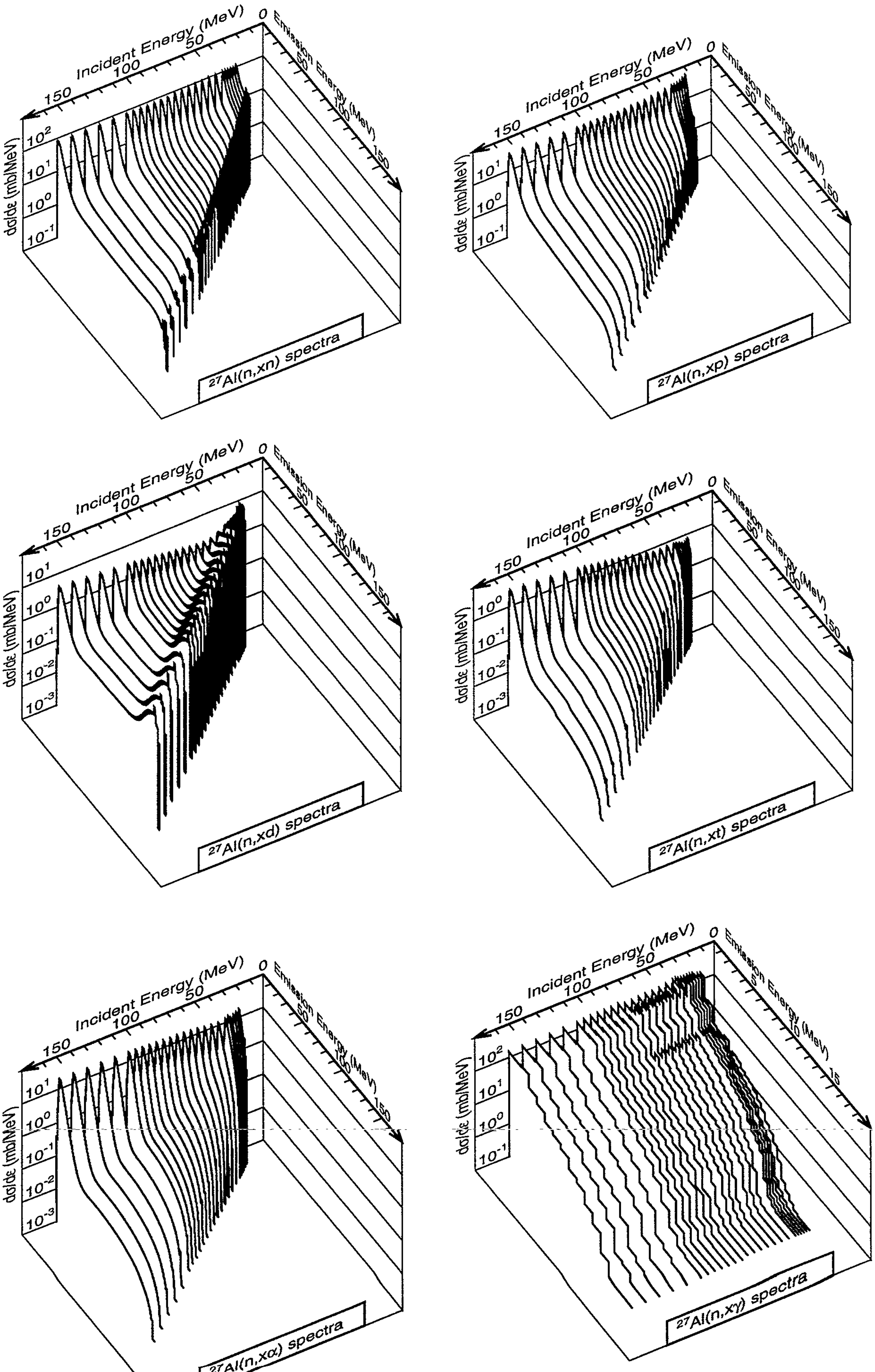
13027 = TARGET 1000Z+A (if A=0 then elemental)
1 = PROJECTILE 1000Z+A
Kerma coefficients in units of f.Gy.m^2:

Energy	proton	deuteron	triton	helium3	alpha	non-rec	elas-rec	TOTAL
2.000E+01	4.625E-01	1.940E-01	6.177E-03	0.000E+00	2.413E-01	2.631E-01	1.003E-01	1.267E+00
2.200E+01	5.263E-01	2.477E-01	9.195E-03	0.000E+00	2.550E-01	2.760E-01	1.015E-01	1.416E+00
2.400E+01	6.014E-01	3.015E-01	1.312E-02	0.000E+00	2.677E-01	2.884E-01	1.021E-01	1.574E+00
2.600E+01	6.740E-01	3.543E-01	1.735E-02	0.000E+00	2.736E-01	2.985E-01	1.022E-01	1.720E+00
2.800E+01	7.265E-01	3.730E-01	2.055E-02	0.000E+00	3.472E-01	3.104E-01	1.013E-01	1.879E+00
3.000E+01	8.054E-01	4.278E-01	2.490E-02	0.000E+00	3.359E-01	3.143E-01	9.974E-02	2.008E+00
3.500E+01	9.948E-01	5.322E-01	3.473E-02	0.000E+00	3.210E-01	3.214E-01	9.592E-02	2.300E+00
4.000E+01	1.147E+00	6.456E-01	4.291E-02	0.000E+00	3.265E-01	3.313E-01	9.067E-02	2.584E+00
4.500E+01	1.324E+00	7.307E-01	4.950E-02	0.000E+00	3.432E-01	3.378E-01	8.466E-02	2.870E+00
5.000E+01	1.468E+00	7.867E-01	5.644E-02	0.000E+00	3.778E-01	3.462E-01	7.956E-02	3.115E+00
5.500E+01	1.631E+00	8.696E-01	6.280E-02	0.000E+00	3.941E-01	3.534E-01	7.421E-02	3.385E+00
6.000E+01	1.809E+00	9.181E-01	6.839E-02	0.000E+00	4.127E-01	3.556E-01	6.940E-02	3.633E+00
6.500E+01	1.972E+00	9.804E-01	7.362E-02	0.000E+00	4.283E-01	3.598E-01	5.912E-02	3.873E+00
7.000E+01	2.141E+00	1.079E+00	7.692E-02	0.000E+00	4.286E-01	3.637E-01	5.403E-02	4.144E+00
7.500E+01	2.314E+00	1.128E+00	8.174E-02	0.000E+00	4.454E-01	3.691E-01	4.932E-02	4.388E+00
8.000E+01	2.509E+00	1.155E+00	8.681E-02	0.000E+00	4.678E-01	3.701E-01	4.504E-02	4.634E+00
8.500E+01	2.738E+00	1.245E+00	8.814E-02	0.000E+00	4.762E-01	3.750E-01	4.104E-02	4.963E+00
9.000E+01	2.967E+00	1.320E+00	9.265E-02	0.000E+00	4.967E-01	3.840E-01	3.753E-02	5.298E+00
9.500E+01	3.204E+00	1.419E+00	9.694E-02	0.000E+00	5.122E-01	3.896E-01	3.424E-02	5.656E+00
1.000E+02	3.417E+00	1.511E+00	1.012E-01	0.000E+00	5.299E-01	3.972E-01	3.131E-02	5.988E+00
1.100E+02	3.876E+00	1.580E+00	1.104E-01	0.000E+00	5.658E-01	4.040E-01	2.608E-02	6.562E+00
1.200E+02	4.283E+00	1.719E+00	1.178E-01	0.000E+00	5.867E-01	4.113E-01	2.248E-02	7.141E+00
1.300E+02	4.706E+00	1.891E+00	1.264E-01	0.000E+00	6.077E-01	4.285E-01	1.949E-02	7.779E+00
1.400E+02	5.191E+00	1.949E+00	1.367E-01	0.000E+00	6.400E-01	4.524E-01	1.630E-02	8.385E+00
1.500E+02	5.644E+00	2.084E+00	1.451E-01	0.000E+00	6.562E-01	4.748E-01	1.441E-02	9.019E+00

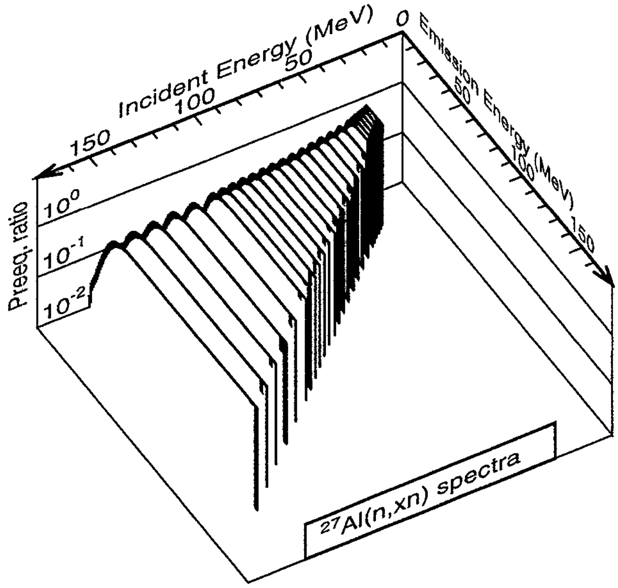
$n + {}^{27}Al$ nonelastic and production cross sections

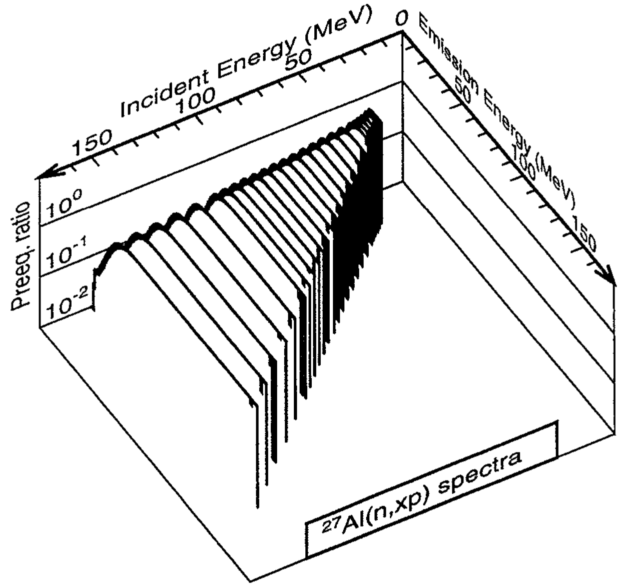


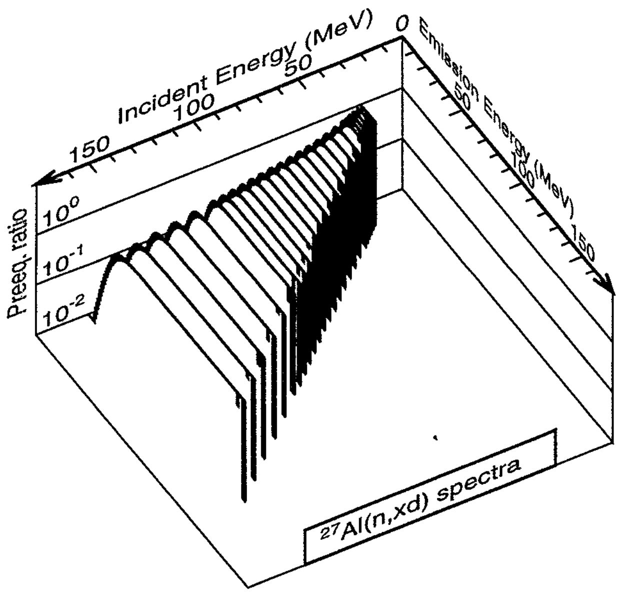
n + ^{27}Al angle-integrated emission spectra

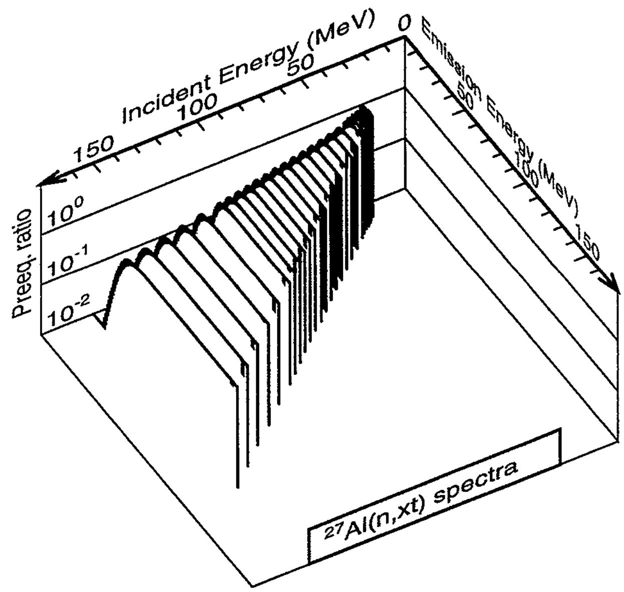


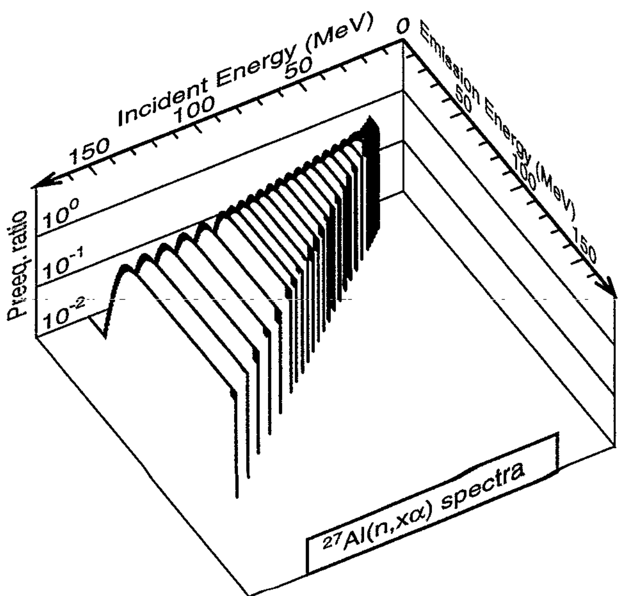
n + ^{27}Al Kalbach preequilibrium ratios

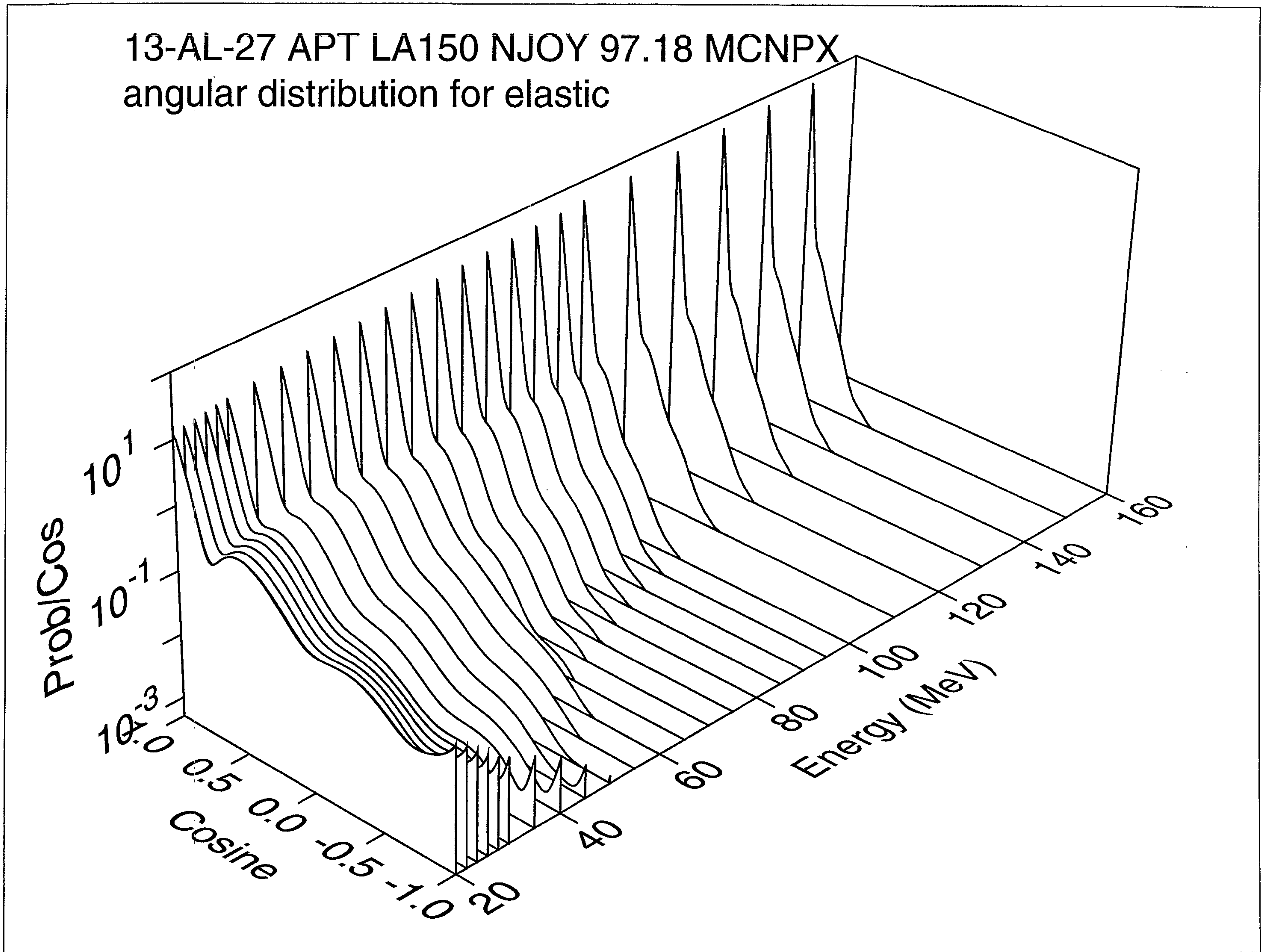




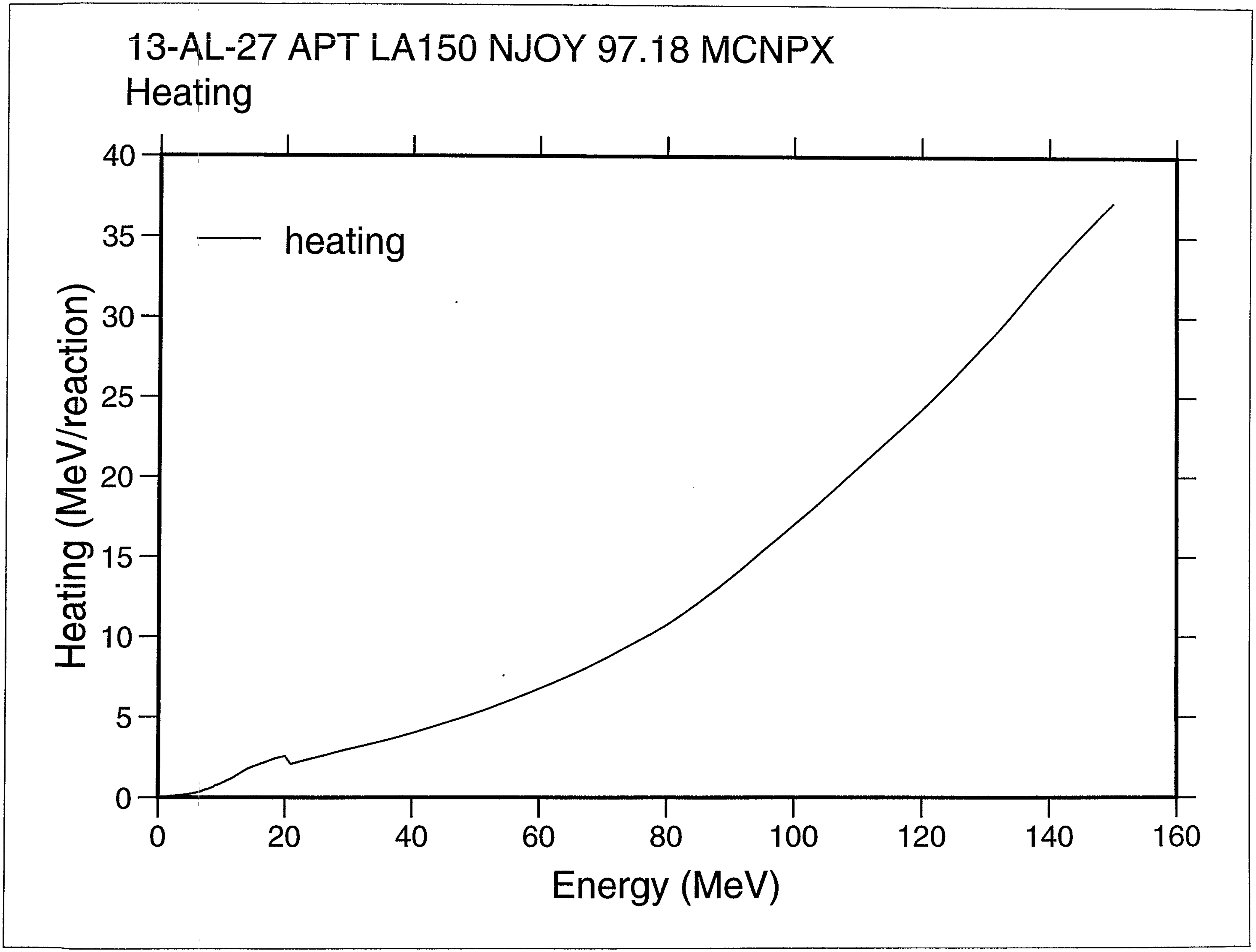


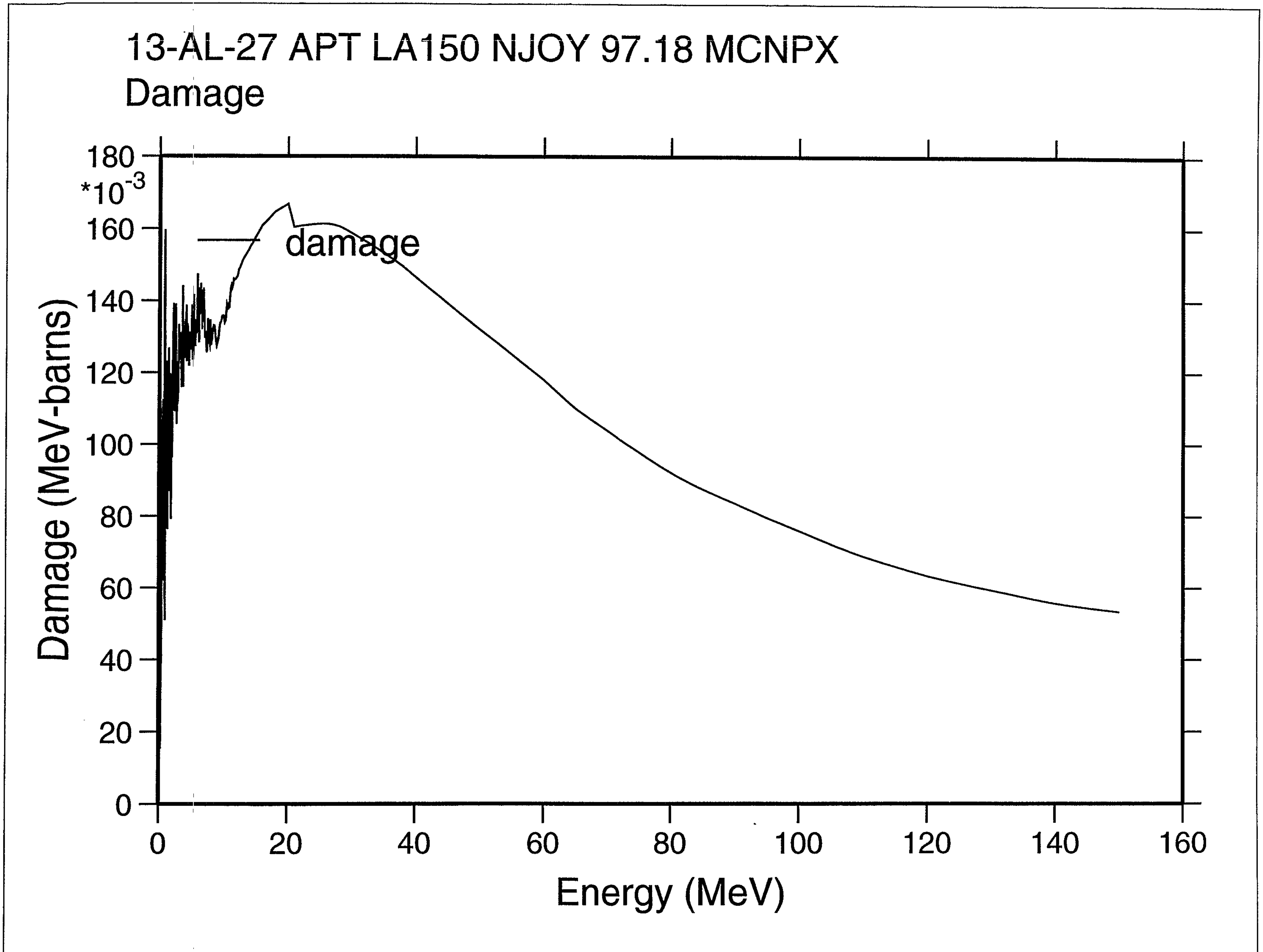






13-AL-27 APT LA150 NJOY 97.18 MCNPX
angular distribution for elastic
Prob/Cos
10^{1}
10^{-1}
10^{-3}
1.0
0.5
0.0
-0.5
-1.0
Cosine
20
40
60
80
100
120
140
160
Energy (MeV)


13-AL-27 APT LA150 NJOY 97.18 MCNPX
Heating
heating
Heating (MeV/reaction)
0
5
10
15
20
25
30
35
40
0
20
40
60
80
100
120
140
160
Energy (MeV)



13-AL-27 APT LA150 NJOY 97.18 MCNPX
Damage
damage
Damage (MeV-barns)
*10^-3
0
20
40
60
80
100
120
140
160
180
Energy (MeV)